THE FOLDING OF SUBJACENT STRATA BY GLACIAL ACTION

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A number of upthrust folds of stratified rocks subjacent to glacial deposits occur at several places in Minnesota. Formerly they were considered as well-recognized glacial phenomena, and accordingly I took no special interest in them. More recently doubt has arisen[1] as to their origin, and this has led to my making a closer study of some of these occurrences. Proof of their true nature as glacial phenomena can now be given. The folds are more or less regular arches from 2 to 30 feet wide, and half as high as wide. The strata of which they are composed belong to the Galena (Trenton) series, or to other formations in Minnesota, which lie as a rule horizontally throughout their extent. The folds and similar displacements are both exceptional and limited to the superficial part of stratified formation, so that no doubt need be entertained as to their being the result of surface agencies.

For example, three such folds were seen in quarries and gradings at St. Paul, Minn., along the 800 foot terrace which runs on the north side of the river from the city to Fort Snelling. This terrace is a limestone bench nearly cleared of glacial deposits by the glacial River Warren. The surface of the limestone lies now generally within the reach of the winters' frosts—i. e., less than 8 feet deep—and the folds in it either lie within reach of frost or may have been in that position at some time in the past. Their origin might therefore be supposed to be due either to the action of frost in water-filled joints of the limestone, or, on the contrary, to the mechanical action of a glacier. Saturation and drying of the strata might also be supposed to have caused them. It was, in short, difficult to prove which agency had caused them.

[1] H. L. Fairchild, "Ice Erosion Theory a Fallacy" *Bulletin of the Geologica Society of America*, Vol. XVI, pp. 12–23.

Two of the same kind of folds have been disclosed more recently in Minneapolis, and these lie in such relations as to show very distinctly their origin from the mechanical action of glacial ice. Since I am now convinced that the folds seen in other places have, with one exception, not been produced by the action of frost, nor by the saturation and drying of the rock strata, I shall describe, for

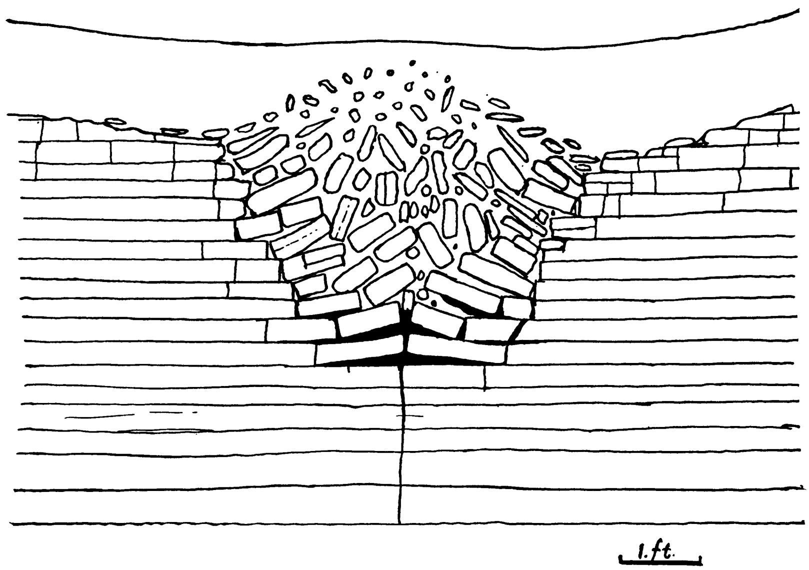

FIG. 1.—Limestone strata upheaved by the freezing of a stream, which now flows under them.

the sake of comparison merely, the one case of undoubted upheaval of a limestone fold by frost and weathering, and then, in particular, the two newly discovered cases of undoubted glacial folding. The case of folding by frost and weathering occurs in the old city quarry at Camden Place, in the northern part of the city of Minneapolis. Here the lowest limestone bed of the Galena (Trenton) series lies near the ground surface, within the reach of frost and humid agencies. A small spring issues from it on the face of a quarry wall, and above the spring the strata and subsoil are seen to be strongly arched (Fig. 1). The origin of this structure is evidently as follows: The stream once flowed on the limestone's surface; annual frosts have heaved the rock-bed so as to let the stream into deeper courses; weathering has aided in loosening the stones and in form-

ing subsoil between them. The folds previously mentioned as seen at St. Paul are dry, and they differ from this one in being more uniform from top to bottom and in the less weathered condition of the stone. They resemble more closely the fold formed by glacial action, which will be next described.

This clearest case of glacial folding occurs at the site of the new lock and dam, No. 1, on the Mississippi River above the mouth of Minnehaha Creek, in the southeastern part of the city of Minneapolis. Here a new roadway is cut down the face of the river's bluff, exposing a fresh section of part of the limestone and shales of the Galena series and of part of the glacial drift. This section of the fold is represented in Fig. 2. The roadway passes the fold twice in descending the bluff in its first case cutting a gravel bed (*I*) and glacial till (*G*) lying over the fold, and in its second cutting obliquely across the fold and part of the undisturbed strata beneath it. From the first cutting the fold can be seen to extend a distance of several rods. The parts represented in the entire section (Fig. 2) are normally:

I.	Glacial gravel	8′
G.	Glacial till	8′
S	5. Gray crystalline limestone	0′ 8″
	4. Green clay-shale	2′ 6″
	3. Gray crystalline limestone	2′ 4″
	2. Green clay-shale	0′ 4″
	1. Dark crystalline limestone	1′ 6″
B.	Massive granular limestone	5′+

When folded up, the stratified rocks which in their normal position would comprise 3 feet of hard crystalline limestone and 2 feet 10 inches of compact clay-shale, or about 6 feet in all, in their disturbed condition make up 15 feet of broken limestone and shales. The overlying glacial deposits are made thinner than they are normally, as shown in Fig. 2. The limestone strata, *S* 1 and *B*, beneath the fold, are not disturbed.

It is evident from the section that the strata which are locally folded were thrust together, sliding upon the clay-shale layer, *S* 2, and that the upheaval resulted from the fracture and upheaval of the resisting layers. The overthrust on the right or northeast side,

and the thinning of the till sheet over the axis of the fold, are thought to indicate that the fold was made under restraining pressure from on top. Since the folding effects the glacial till (*G*), and the gravel (*I*), is thinned over it, it was evidently made later than the time when the till was deposited, and perhaps later than the deposition of the gravel. A glacier has undoubtedly crept over this place

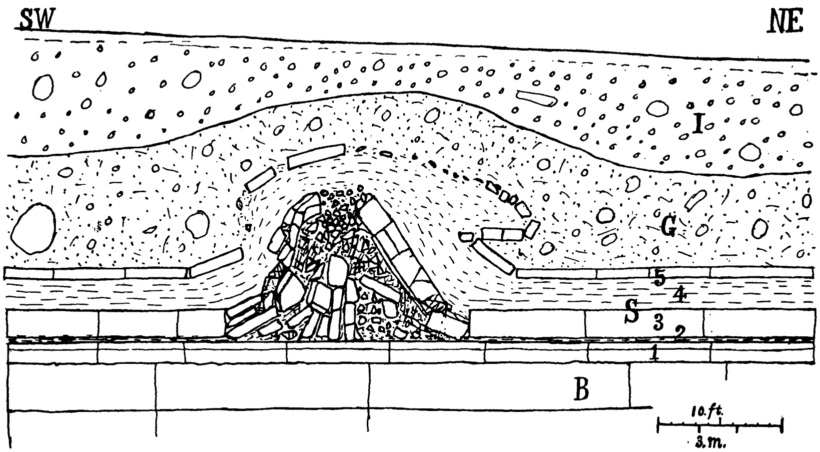

FIG. 2.—Profile of a fold in stratified rocks under glacial deposits.

within this period, as proved by its deposits, although these are absent from this particular spot, presumably because the glacial river Mississippi has cut away the upper sheet of till. Other sections in the same region show the till of the later glacier. It may be assumed, therefore, that glacial ice moving over the till bed, and perhaps over the gravel bed (*I*) gave the thrust that upfolded the limestones and shales at this point.

How the glacial ice could do such heavy crushing of crystalline limestones may perhaps be explained by the friction of the glacier upon the field of gravel, which for a considerable area could accumulate great stress and transmit it to the subjacent strata sufficiently to cause the upper stratified rocks (*S* 3–5) to glide along a clay seam (*S* 2), and thus converge the power of a large portion of the glacier upon a small part of the rock strata. This hypothesis is the more plausible since in some places in this region the gravel bed rests immediately on the stratified rocks.

Why the rock was crushed and folded at this place rather than at any other is not evident in this exposed section. The reason is explained by another case which occurs four miles farther up the river's bluff, in the quarry next to Riverside Park. This case is shown in Fig. 3. The section here shows the following:

G.	Glacial till and soil . . . . about	10′	
S	6. Green clay-shale	3′	
	5. Gray crystalline limestone	0′	6″
	4. Green clay-shale	1′	
	3. Gray crystalline limestone double stratum . .	2′	4″
	2. Clay-shale, irregularly laminated	0′	4″
	1. Dark crystalline limestone	1′	4″
B.	Massive granular limestone	4′+	

Since the till in this section now forms an ancient terrace of the river, it evidently has not its original thickness. Below the till the same rock strata appear as in the other section (Fig. 2) and therefore the parts of Fig. 3 are littered in the same order as those of Fig. 2. The main stratum (*S* 3) appears double here because of a thin irregular shaly lamina within it.

The noteworthy feature in the section is the reversed fault which appears in the top part of the main stratum (*S* 3). The fault is clearly the result of thrust and displacement along an oblique joint. The overlying strata are disturbed by lateral compression and by upward movement of the faulted piece, while the underlying strata are not disturbed. The phenomenon can be explained as the result of glacial friction upon the stratum at a distance from the point of faulting, causing the stratum to move from right to left—i. e., northwest to southeast—as far as the line at which an oblique joint in the rock led to its development of a fault. The fault, as seen on the surface of the rock, which has been cleared of drift in the quarry, runs from northeast to southwest in a reversed curve for about 40 feet. It extends indefinitely farther.

This and the previously described case may be considered as two stages of the same process of folding. Although they were probably not made by the same glacier, at the same time, since the strike of the one is nearly at right angles to that of the other, yet they occur in the same strata under the same till-sheet. Com-

paring Figs. 2 and 3, and noting that the direction of movement is from left to right in Fig. 2, and from right to left in Fig. 3, one can see how upfolding may be begun, and to what extent it could quickly develop in strata subjacent to a glacier which moved over a till- and gravel-covered surface. Why the disturbance ceased just where it did in either of these cases is not evident.

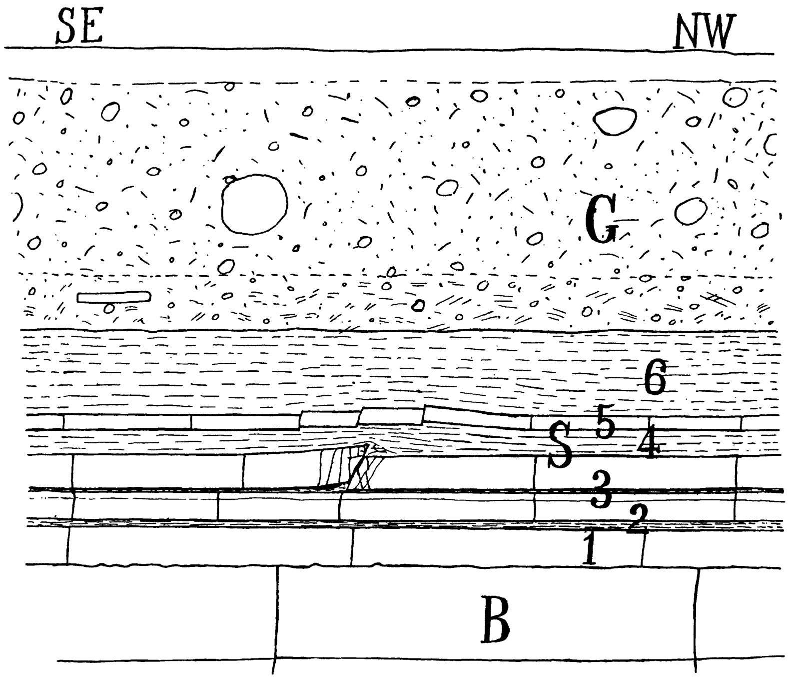

FIG. 3.—Profile showing a thrust fault in strata under till.

I imagine no other cause for the starting of the fold represented in Fig. 2 than that seen in the fault, Fig. 3. The stratified rocks in both places are fresh and not oxidized. In some other cases the cause may have been a little different, especially in the ones mentioned as seen in St. Paul, where there was much evidence of leaching and oxidation by surface water, and where the folds were of limestone strata alone. Those were each immediately over a vertical joint of the rock and contained some residuary clay. From these circumstances it appears that they may have been begun by the sliding of superficial strata toward a widened joint which had

filled with residuary clay, and that the lateral compacting of the clay gave the initial upward thrust. The folds had, however, progressed too far for the conditions of their first stages to be discernible. The presence of residuary clay gave them some resemblance to the case of upfolding by frost as described (Fig. 1).

Regarding the general manner of upthrusting, presumably any weakness of rock structure could serve to determine the point where a folding of strata would begin. The other conditions for such folding are first a seam along which the strata might be caused to slide, and then the force necessary for such movement. This force appears to come through a gravel bed from a moving glacier.

In a former article[1] I have described a similar dislodging of stratified rocks, in a way which caused large masses to be rotated up into the glacier, and thus transported without complete loss of stratification. In the cases now described, the tendency is rather toward complete loss of stratification. One may readily imagine from the appearance of the fold (Fig. 2) that in nearly all such cases the disturbing of the strata when once begun, would end only with complete disruption of the loosened mass and an intimate mixture with glacial gravel and till. Many masses occur in the drift of this region which consists largely of crushed stone and shales with the colors and characteristics of the known stratified rock, but without the stratification or the fossils preserved in them.

[1] *Journal of Geology*, Vol. XIII (1905), p. 351.